Remote Sensing of Cloud Icing Potential

The need to support the safety of aircraft in a growing technological society requires continuous innovation. The safety of these aircraft is paramount and therefore the detection and prevention of aircraft icing is of great importance. There are many ways to prevent or remove ice from aircraft once icing has begun but prior knowledge of potential icing conditions is critical if these systems are to be utilized effectively. Satellite imagery is the best way to quickly gain significant amounts of information on potential icing conditions over a wide spread area.

First of all an understanding of where icing potential exists in the vertical profile of a cloud is needed. From the figure below (Figure 1), the location of possible icing conditions can be readily identified.

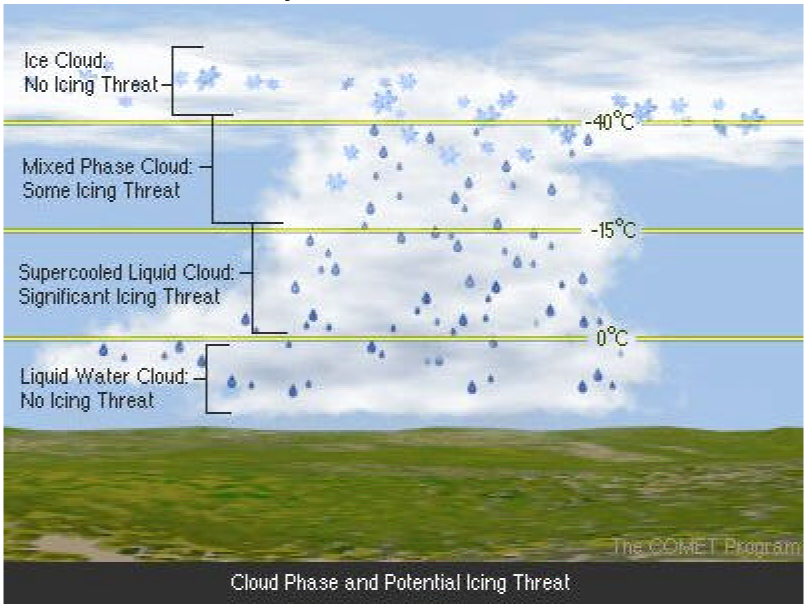

Figure 1 (http://meted.ucar.edu/icing/pcu62/pcu621/index.htm)

In the lowest part of the cloud, the part of the cloud that is below the freezing level is composed entirely of water droplets and no icing potential exists.

The second temperature level of the cloud is above the freezing level and contains supercooled liquid water droplets. The cloud droplets in this region are suppercooled because of the fact that cloud droplets do not freeze without a proper ice condensation nucleus. This is always the case for cloud droplets unless the temperature is less than –40°C which is the homogeneous freezing threshold for water. Therefore, significant icing is possible in the second temperature level of the cloud.

In the third cloud layer, where temperatures are less than -15°C, freezing of cloud droplets begin to dominate, but there is still some supercooled liquid remaining. Therefore, the icing threat is lower in this layer since the liquid water content is lower.

In the highest part of the cloud temperatures are below -40°C, and no liquid water can persist so the icing threat is essentially zero.

Understanding where supercooled liquid water (SLW) can occur in a cloud and at what temperatures is the 1st step in developing an algorithm that detects SLW remotely. The next step is to develop an understanding of the way Geosynchronous Operational Environmental Satellite (GOES) information is utilized to "see" probable areas of icing conditions. These satellites measure the brightness of the earth's atmosphere and surface. The brightness data that is measured is then converted over to a temperature scale in degrees Celsius. The GOES spacecraft are designed to measure visible (0.6 microns), shortwave IR (3.9 microns), water vapor (6.7 microns), and longwave IR (11 and 12 microns). A breakdown of the appropriate use of the GOES wavelengths (channels) is given below.

GOES Channels and their uses in icing detection:

Channel 2 on the current GOES satellites (GOES - 8/9/10) gives a shortwave infrared image that is centered at about 3.9 microns and contains both reflected solar energy **and** emitted terrestrial energy. Since this wavelength contains reflected solar energy, it cannot be directly related to cloud-top temperature. Therefore channel 2 is not very useful if used alone. However, when used in multispectral analysis (i.e., 2 or more wavelengths), it can provide a great deal of useful information.

The subtraction the two longwave infrared wavelengths (channel 5 data from channel 4) is known as Brightness Temperature Difference. Channel 5 is called the Split-Window IR channel and it is centered at 12 microns while Channel 4 (the standard IR channel) is centered at 11 microns. Optically thin clouds emit different amounts of energy at these two wavelengths, and clouds that are optically opaque emit the same amount of energy at these wavelengths. Therefore, the subtraction of these two channels allows regions of thin clouds (cirrus) to be displayed.

In the discussion above concerning the 3.9 micron shortwave IR channel it was stated that the shortwave IR channel is sensitive to both reflected and emitted IR energy. Solar reflectance at 3.9 microns depends on many things including the relative angle between the sun, clouds, and satellite (solar zenith angle) as well as the reflecting material. The difference in the reflectance properties of water and ice is most useful here. The technique described in the next paragraph allows for the discrimination between clouds composed of water versus those composed of ice particles.

Clouds that are composed of water generally reflect more shortwave IR energy than clouds that are composed of ice. The amount of reflection depends on the size of the water droplets and/or ice particles. However, at night solar reflection is not a contributing factor in the measurements and the differences between water and ice/snow are due solely to emission. Water droplets emit less energy at 3.9 microns than they do at 11 microns while ice particles emit about the same amount at the two wavelengths.

Therefore subtracting the 3.9 micron shortwave IR channel from the longwave IR channel allows for the determination of whether a cloud is composed of water or ice. This technique is also useful for detecting low stratus clouds and fog.

A shortwave IR reflectance product has been created via multispectral analysis that uses radiative transfer theory to derive a new product from other data. This is not a GOES channel but it is a product of raw data obtained from the GOES channels. This product enhances the difference between the shortwave and longwave IR data by isolating the solar reflectance at 3.9 microns and eliminating the emitted component. As mentioned earlier this technique is valuable in discriminating between water and ice/snow clouds. When used with temperature data the image produced by this technique indicates regions of supercooled liquid water, and hence regions of possible aircraft icing hazard.

<u>Aircraft Icing Product</u>:
This product is created with all of the data and products mentioned above. This information is then used together to determine areas of supercooled liquid water (i.e., clouds composed of <u>water</u> drops which are below 0°C). Images of these areas are highlighted in blue and they represent possible icing hazards to aircraft. These areas represent "potential" icing regions since different types of planes are affected differently by supercooled droplets. If, for a given pixel, the preset icing conditions are not met for the Icing Product, a standard visible or IR image is shown in its place depending on whether it is daytime (visible) or nighttime (IR).

The following image (Figure 2) is a small example of the satellite derived aircraft icing product. The image shows clouds tops over MSP (**M**inneapolis/**S**t. **P**aul) that have radiative patterns which indicate a high probability of SLW. The blue areas are areas of supercooled liquid cloud tops indicating clouds that have a high likelihood of containing icing conditions.

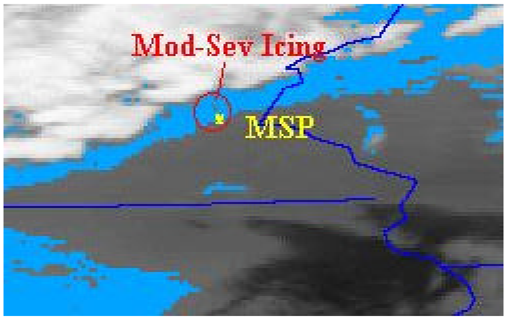

Figure 2

<u>Icing Product Advantages</u>:
1) Satellite data can readily determine horizontal areas in which icing is impossible, such as cloud-free regions and areas that are above the freezing level.

2) Satellite infrared data determine vertical (above cloud) areas where icing is impossible.

3) The GOES systems have very high spatial of 1 to 4 km for VIS and IR respectively, as well as high temporal (15-30 min) resolution.

Icing Product Limitations:

1) This technique is still *experimental* and further testing is necessary before it can be used operationally. This technique is primarily being developed by the Research Applications Program (RAP) of the National Center for Atmospheric Research (NCAR).

2) Satellite derived icing techniques are only useful for diagnosis of icing hazards, and cannot be used to predict anticipated icing hazards.

3) The algorithm cannot detect low altitude SLW cloud tops which are obscured by high level, low temperature clouds (e.g., cirrus). The algorithm is also limited in areas that are covered by deep convective clouds. Extremely cold cloud tops are often associated with convective clouds (thunderstorms) that may contain strong icing conditions. The icing in these situations is due to the fact that SLW often exists at very cold temperatures in regions of strong updrafts. The liquid cloud droplets in these updrafts do not have enough time to find an appropriate ice condensation nuclei and are therefore often encountered in a supercooled liquid state. See Figure (3) below.

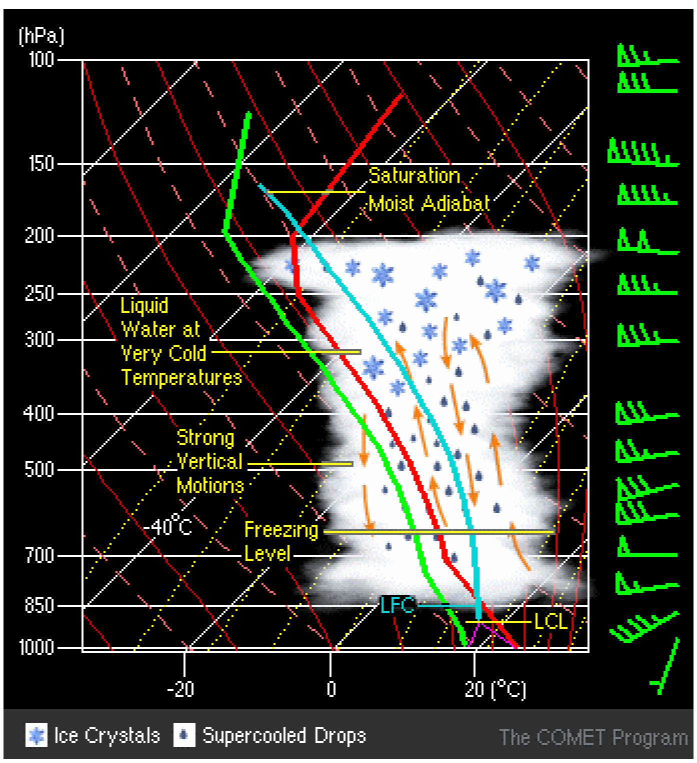

Figure 3 (http://meted.ucar.edu/icing/pcu62/pcu621/index.htm)

4) Due to the strong solar zenith angle dependence of the 3.9 micron channel the images are not effective in regions near sunrise and sunset. Data for these transitional situations is displayed on the image as a distinct, nearly vertical line close to sunrise/sunset. This can be seen in the figure below (Figure 4) as a blue line running across the continental U.S. from Louisiana to the eastern side of the Great Lakes.

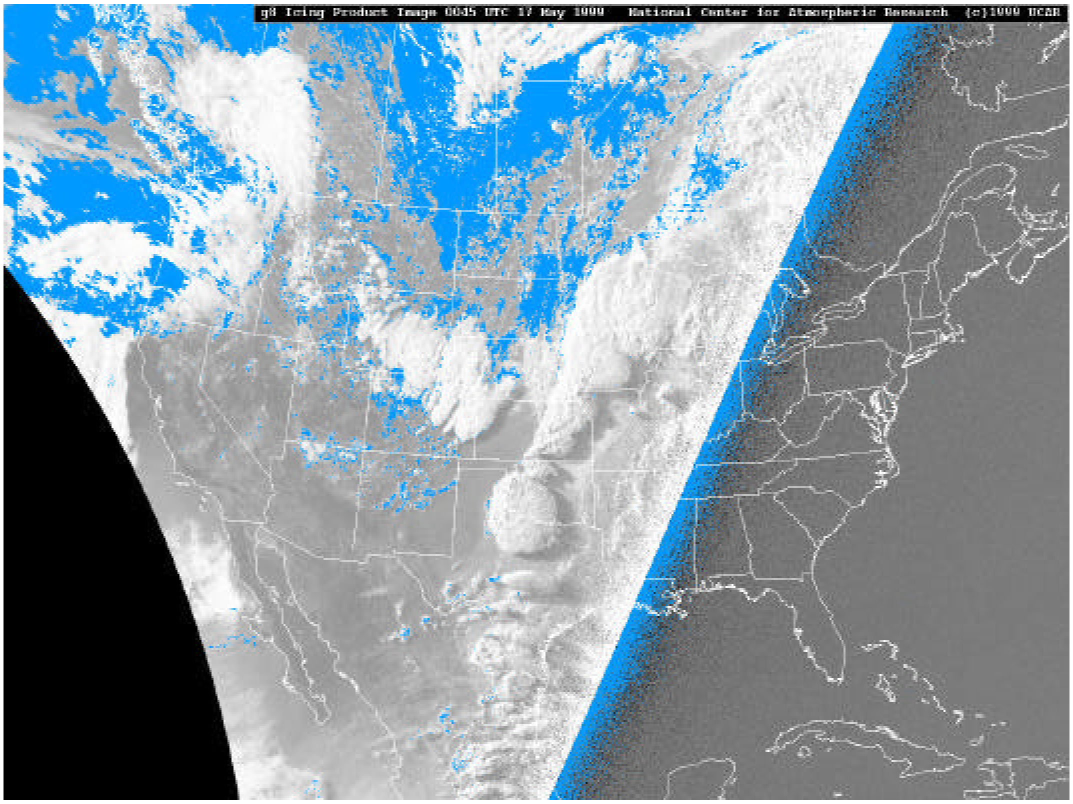

Figure 4 (http://www.rap.ucar.edu/largedrop)

Closer inspection of Figure 4 in the area over Texas shows how deep convective clouds can obscured the icing conditions within them. This is illustrated below (Figure 5) where, due to the strong westerly wind over the area, the high SLW content and therefore high icing probability (blue) can be seen upwind of a convective plume.

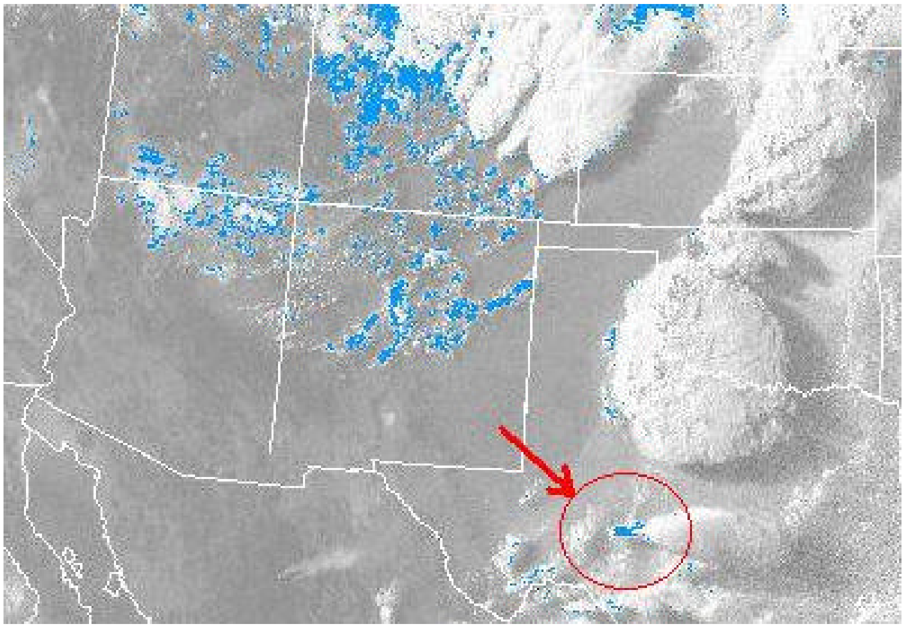

Figure 5 (http://www.rap.ucar.edu/largedrop)

<u>References</u>:

http://meted.ucar.edu/icing/pcu62/pcu621/index.htm

http://www.rap.ucar.edu/weather/satellite/multispectral.html

http://www.rap.ucar.edu/largedrop

Thompson, G., T.F. Lee and J. Vivekanandan, 1997: Comparisons of satellite-based aircraft icing diagnoses. To be presented at and included in the preprints for the 7th Conf. on Aviation, Range and Aerospace Meteorology, 2-7 February, Long Beach CA, Amer. Meteo. Soc.

Vivekanadan, J., Thompson G., T.F. Lee, 1996: Aircraft icing detection using satellite data and weather forecast model results. FAA International Conference on Aircraft Icing, Springfield, VA, 6-8 May.